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General Atomics Smart Microsensors — FY05 Laboratory Fire Test Results

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14. ABSTRACT

This report describes the cermet sensors and system control software recently evaluated in laboratory tests for shipboard damage control. The tests were conducted to generate a database of sensor responses to fire and nuisance sources for algorithm development, and to develop fire detection alarm algorithms. In this work, the cermet sensors incorporate four sensors with multivariate analysis methods and classification algorithms for detecting a wide variety of analytes, including toxic industrial chemicals, fires, and nuisance sources. The test series successfully demonstrated the functionality and performance of the microsensor system for use in fire detection. The detection system demonstrated the ability to detect flaming and smoldering fires at the same level as the commercial multicriteria detector. It was on average 2.5 to 5.5 minutes faster for smoldering fires, vs. all detector types evaluated, and 50 to 80 s faster for flaming fires, vs. multicriteria and photoelectric detectors, but 50 s slower than the ionization detector. The system needs improvement in addressing fire-like nuisances.

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Cermet sensor; Fire detection, Multivariate data analysis; Pattern recognition; Cyclic voltammetry, Microsensor arrays; Sensor arrays

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GENERAL ATOMICS SMART MICROSENSORS – FY05 LABORATORY FIRE TEST RESULTS

1.0 INTRODUCTION

Cermet sensors are a combination of ceramic and metallic materials and have been used in electrochemical sensing applications for decades. Most automobiles have oxygen sensors consisting of YSZ (yttria stabilized zirconia) sandwiched between Pt electrodes. Recently General Atomics (GA) has been developing cermets for chemical sensing applications. They are capable of high temperature operation and are used as electrodes to perform electrochemical cyclic voltammetry on gases. A natural extension of this is to fabricate cermet arrays and have the output fed into microelectronic readouts. Cermets can be fabricated using both thick film and thin film techniques. Also, tailored devices are possible because different cermets respond to the same gas in different ways. This adds design flexibility.

Voltammetry is a very well-established chemical analysis technique that is particularly flexible and capable of very low level detection (part per billion) for organic, metallic, and organometallic substances in experiments using aqueous electrolytes. In the gas phase experiments using solid electrolytes that are employed in this work, detection levels in the low parts per million range without using concentrators are observed. The waveform contains a great deal of information, for example, peak position, height and shape that can be exploited for analytical purposes.

The chemical microsensors offer a small size, lightweight and low cost alternative to conventional electrochemical (EC) sensors. When combined with pattern recognition software, these smart microsensor arrays provide a sensor/data analysis system to detect a wide variety of analytes. The chemical microsensor architecture is modified for detection selectivity of a variety of chemical agents and combustible or corrosive gases. As such, the microsensor arrays have potential application for monitoring hazardous chemicals in the parts-per-million to parts-per-billion range in a variety of internal and external environments. The sensor arrays will sense analytes of interest using pattern recognition techniques to determine the presence of gases.

With the advances in detection technology and the move towards increased automation on ships, the Navy has sought fire detection systems capable of improved performance over conventional smoke detectors. The Early Warning Fire Detection System (EWFD) developed under ONR's Damage Control Automation for Reduced Manning (DC-ARM) program has shown that multicriteria detectors can provide improved performance over conventional smoke detectors, faster response to fires and better nuisance alarm immunity [1-4]. A similar effort that originated out of the DC-ARM program was the development of a smart chemical microsensor array by General Atomics (GA) [5]. The goal of the chemical microsensor array was to provide a small, lightweight, low-cost alternative to conventional sensors. To demonstrate this concept, a GA Smart Microsensor was exposed to a variety of burning materials onboard the ex-USS *Shadwell* from August 31 to September 2, 1999. Data from these sensors was post-processed using a neural network algorithm that was supplied with a synthetic training data set. These tests illustrated the potential of the GA Smart Microsensor to provide highly successful fire classification.

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In addition to providing fire detection capabilities, this technology was developed for the detection of Toxic Industrial Chemicals (TICs), chemical warfare agents including blood agents under the sponsorship of the Science and Technology Chemical and Biological Defense Program (S&T CBDP) from 2002-2004. Recent studies have investigated sensor arrays consisting of four cermet sensors fabricated on a ceramic substrate with the following composition. Sensor A: platinum – yttria stabilized zirconia - platinum-palladium (Pt–YSZ–Pt/Pd), Sensor B: platinum – yttria stabilized zirconia - platinum (Pt–YSZ–Pt), Sensor C: platinum-yttria stabilized zirconia – platinum - tungsten bismuth oxide (Pt–YSZ–Pt–WBO), and Sensor D: platinum – yttria stabilized zirconia – platinum/palladium – tungsten bismuth oxide (Pt–YSZ–Pt/Pd–WBO). The sensors were evaluated with known concentrations of analyte gases and vapors in humid air. Carbon monoxide, ammonia, sulfur dioxide, hydrogen sulfide, carbon disulfide, benzene, formaldehyde, chlorine, hydrogen chloride, hydrogen cyanide, cyanogen chloride, dimethyl methyl phosphonate and diisopropyl methyl phosphonate, and 2-chloroethyl ethyl sulfide were tested at 10, 25, 50, 100, and 200% of the TLV levels. [6]

In this work funded by the Office of Naval Research, smart chemical microsensor arrays are being further developed and evaluated for shipboard damage control. Two test series have been completed. In April 2004, a full-scale laboratory test series was conducted using an updated version of the GA microsensor array. The primary goal was to expand the fire and nuisance source database for algorithm development [7]. In October 2004, a full-scale shipboard test was conducted on the ex-USS *Shadwell*. The detection system was modified to run off of one personal computer using a network of detectors. The sensor formulations were also modified. The network and system software was a success; however, the new sensor formulation provided disappointing results. The new sensors did not possess the desired sensitivity and were not compatible with the algorithms that had been developed to identify the fires and nuisance sources. Based on this work, new sensors were developed using the earlier successful formulations. The latest version of the sensors and system control software will be evaluated in laboratory tests to generate a database of sensor responses to fire and nuisance sources for algorithm development prior to the shipboard tests. This data will be used to develop fire detection alarm algorithms.

This report describes the latest version of the sensors and system control software recently evaluated in laboratory tests. The tests were conducted to generate a database of sensor responses to fire and nuisance sources for algorithm development, and to develop fire detection alarm algorithms. In this work, the cermet sensors incorporate four sensors with multivariate analysis methods and classification algorithms for detecting a wide variety of analytes including TICs, fires and nuisance sources. The full-scale, laboratory fire tests were conducted during April to June 2005.

2.0 OBJECTIVES

The objective of this work was to evaluate the smart microsensor arrays and the pattern recognition methods for fire detection in the shipboard environment. The tests will also be used to expand the database of sensor outputs from the GA microsensor array. This database was used post-test to evaluate the performance of the developed fire detection alarm algorithms and provide a basis for further refinement.

3.0 APPROACH

The objective was achieved by conducting full-scale experiments in a ship compartment and passageway mock-up in the Baltimore laboratory of Hughes Associates, Inc. (HAI). The various smoke detection technologies under evaluation were installed in the compartment and passageway mock-up and exposed to a broad range of fire and nuisance sources. The performance of the GA smart chemical microsensor arrays was compared to standard single-sensor smoke detectors and the multi-criteria smoke detectors.

4.0 EXPERIMENTAL SETUP AND PROCEDURE

The tests were conducted in a test facility measuring 10m x 10m (33 x 33 ft). The facility consists of 3 compartments and a passageway, Fig 1. Sources were not initiated in the adjoining spaces to the largest compartment; however, the compartments were open allowing smoke spread and natural ventilation to occur. GA sensors were mounted in the nominal 9 x 6 x 3 m (29 x 20 x 10 ft) compartment and the attached passageway. Figure 2 shows the layout of the spaces that were used for the tests. A summary of the test setup is provided in the following sections.

4.1 Test Spaces

The dimensions of the spaces are shown in Fig. 2. The ceiling is 3.0 m (10.0 ft) above the deck in both the compartment and passageway. The compartment contained simulated overhead beams constructed of steel sheeting; the passageway had a smooth overhead. The simulated beam obstructions were secured to the overhead of the compartment at a spacing of 1.2 m (4.0 ft) and a depth of 31 cm (12 in.). The compartments contained multiple obstructions such as electrical cabinets, light fixtures, and office equipment, Figs. 3 and 4.

The test compartments were located in a working laboratory/warehouse facility. The laboratory was conditioned by a heater and indirectly by the adjoining office space. However, the laboratory was frequently opened to the outside via rollup delivery doors. Therefore, conditions varied depending in part on outdoor conditions and the use of the exterior doors.

4.2 Ventilation and Closures

The majority of tests were conducted with mechanical ventilation and with all interior doors and the exterior doors of the facility open. Supply air consisted of natural draw from the laboratory through the two open exterior doors of the test facility, Fig. 1. A schematic of the ventilation ductwork is shown in Fig. 5. The ventilation duct was run below the simulated beams in the test compartment. The ventilation duct was exhausted through a fan

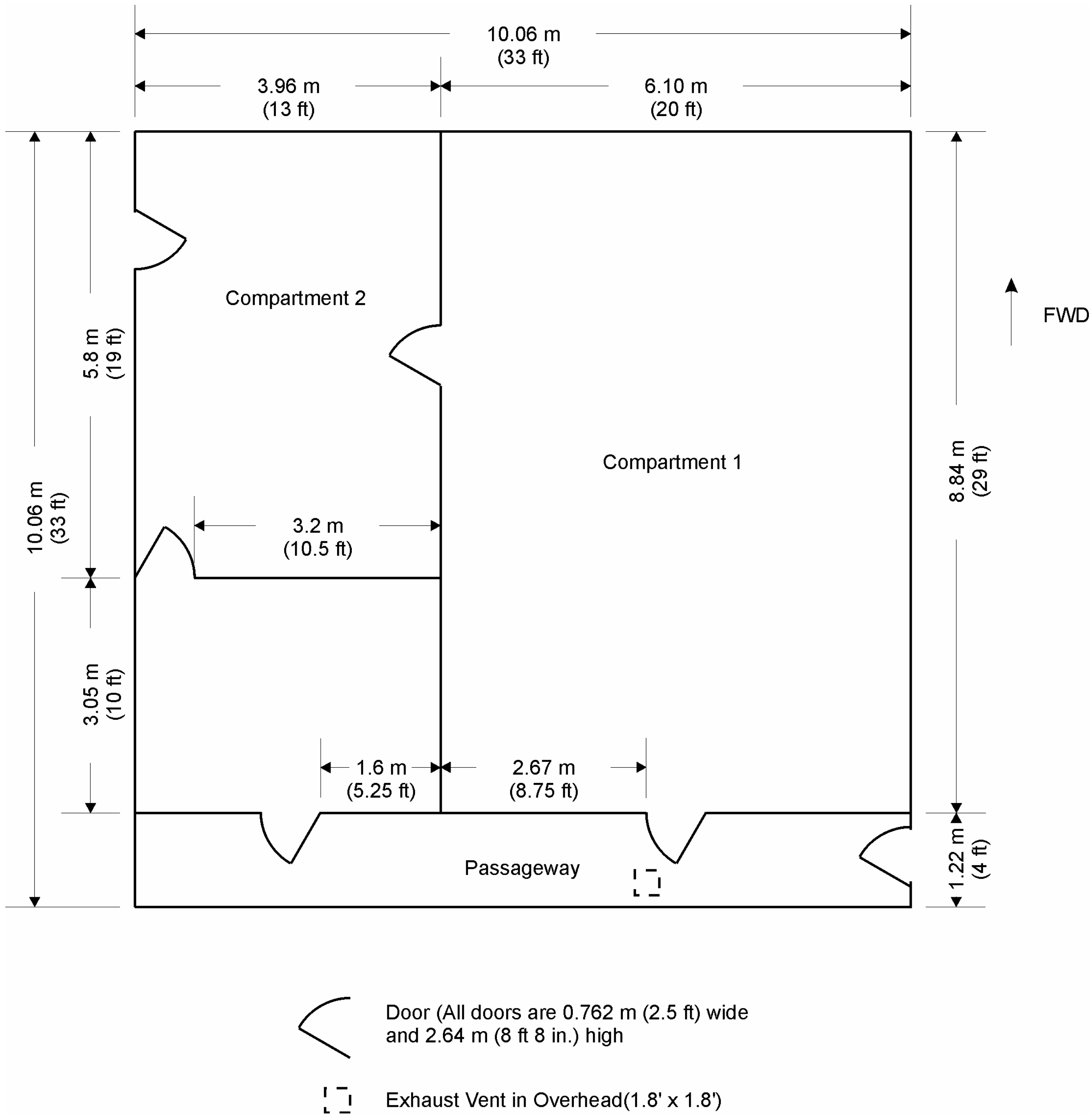

Fig. 1 — Test facility plan view

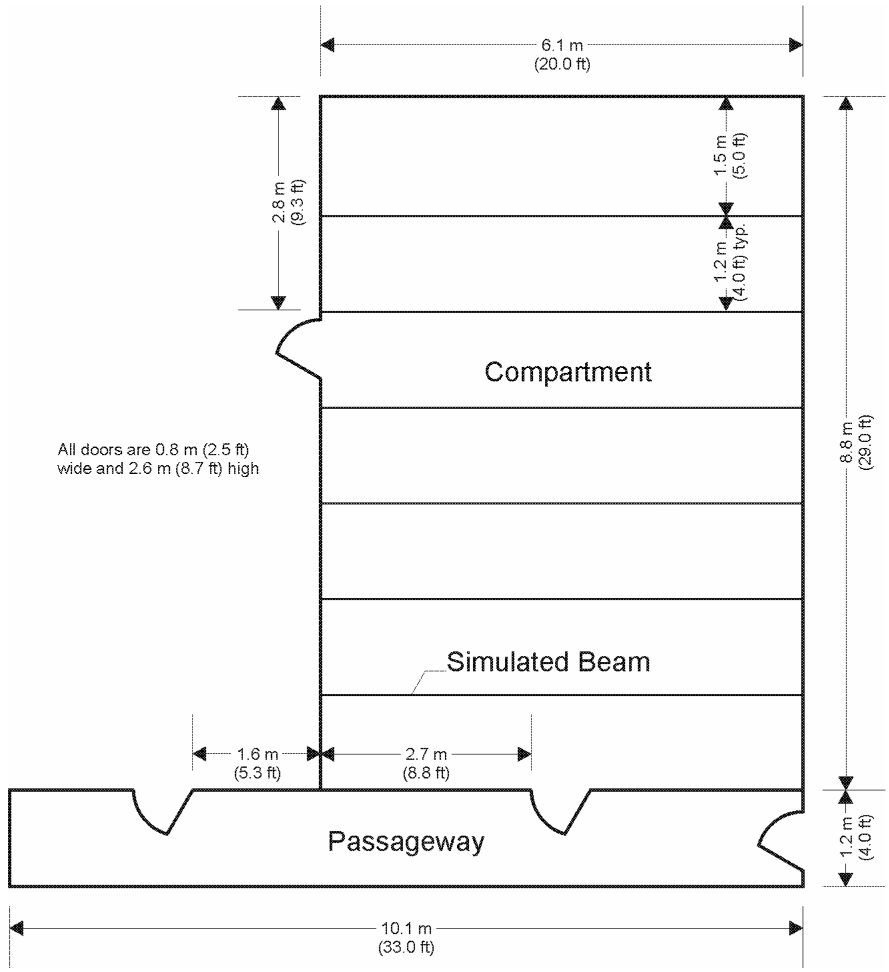

Fig. 2 — Test spaces

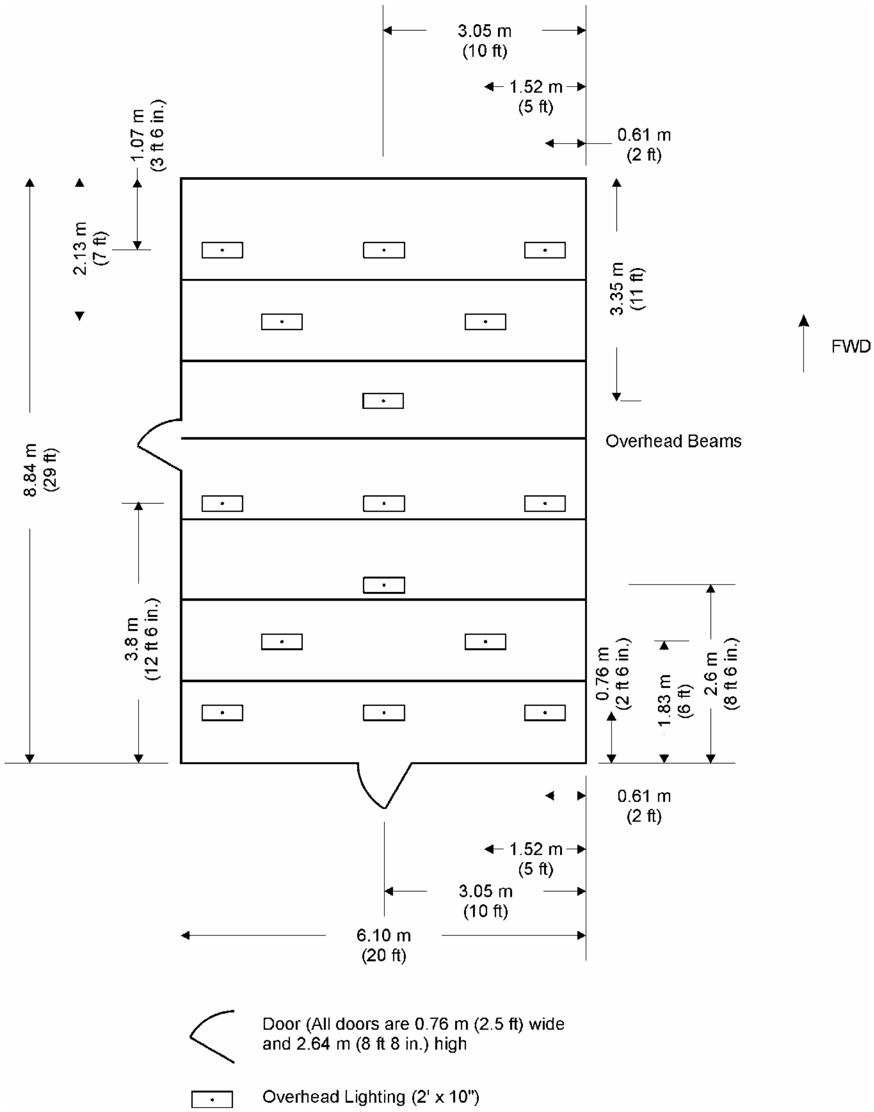

Fig. 3 — Overhead obstructions within test compartment

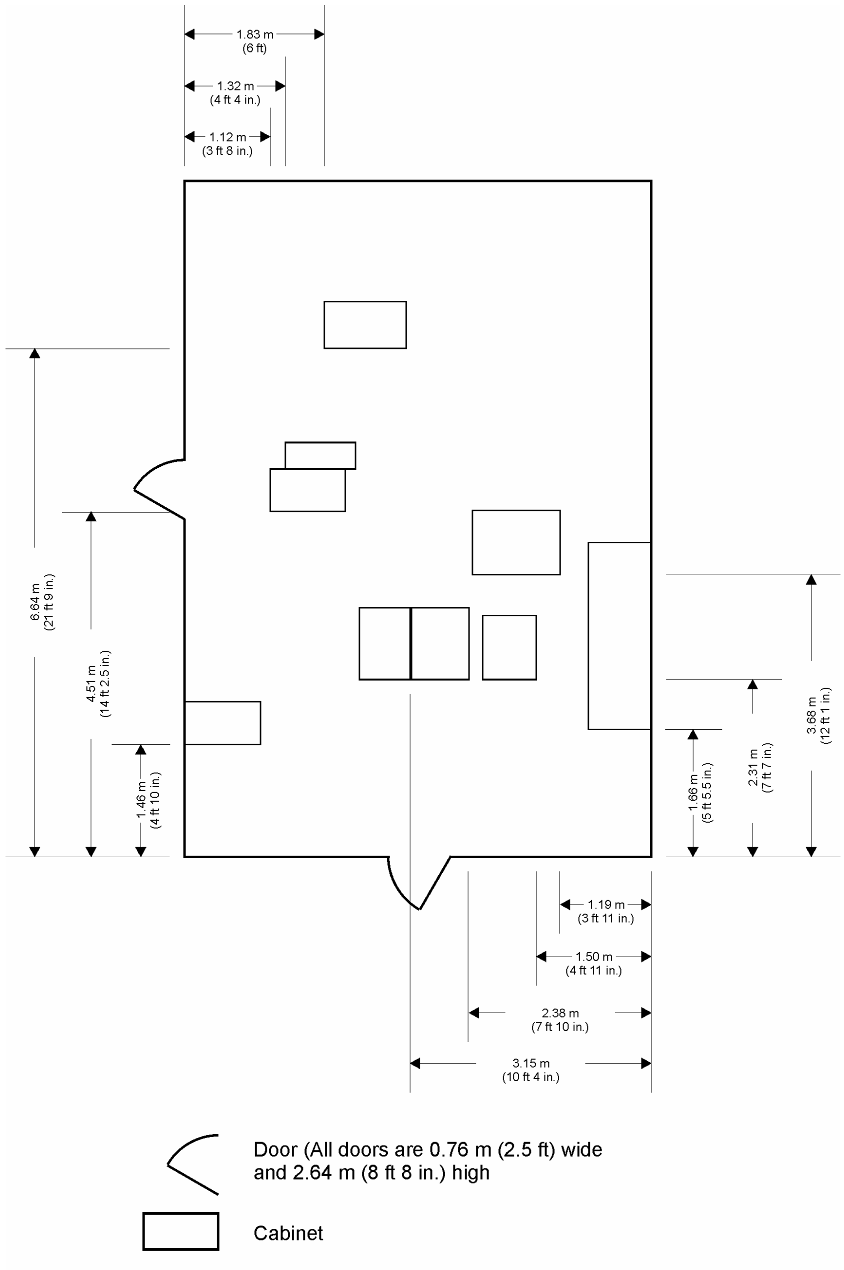

Fig. 4 — Obstructions within test compartment

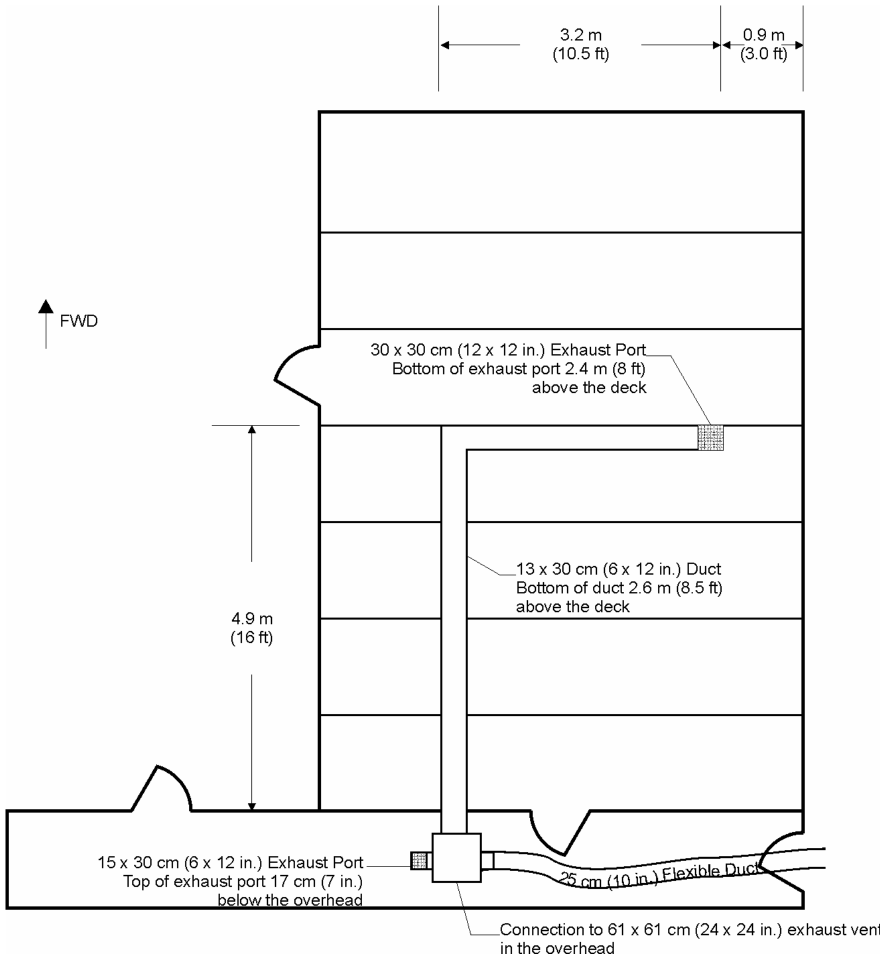

Fig. 5 — Ventilation schematic

with a maximum flow rate of approximately 1.2 m^3/s (2500 cfm). Given the total volume of the large compartment and passageway (201 m^3 (7120 ft^3)), the system can provide a maximum of 21 air changes per hour. Bypass flows and dampers were used to provide approximately 4 to 5 air changes per hour (ACH) in the large compartment, as is typically found on Navy ships [8]. A length of flexible duct was attached to the system and run out of the test facility to bypass flow and to reduce the rate of air exchange within the test compartments.

4.3 Fire and Nuisance Sources

Fire and nuisance sources were created to expose the detection systems to a range of potential shipboard scenarios. Small fires were used to challenge the detection systems and to provide performance results for early detection. The selection of sources was based on previous studies conducted for the Navy [4, 9]. Tables 1 and 2 present the fire and nuisance sources that were used in this test series. The source locations are shown in Fig. 6. Locations 1 and 2 were used for fire sources, while Location 4 was only used for nuisance sources. Certain sources, such as the electrical cable fire, were conducted in the overhead to be representative of shipboard configurations.

Table 1 — Fire Sources

No.	Fire Source ID	Description
1	Flaming Cardboard Box	A two-tiered stack of four boxes 0.26 x 0.26 x 0.11m (10 x 10 x 4.5 in..) will be loosely filled with brown paper (1.1 m x 0.6 m) and positioned with a 2.5 cm flue space between the two stacks. A butane lighter will be used to light a bottom corner of a box in the flue space so that flames propagate up the flue space and involve both boxes.
2	Flaming Trash Can	One 61 x 84 cm O.D., 32 L, 6µm (24 x 33 in.. O.D., 12-16 gal) plastic trash bag will be filled with ordinary office trash (10 sheets printer paper, 20 crumpled, brown paper towels, bubble wrap (1 ft x 4 ft), four FedEx letter mailing packs, five polystyrene plastic cups) and placed in a metal trash can. The open bag of trash will be lit at the top with a butane lighter.
3	Flaming Mattress and Bedding	One 0.3 x 0.3 m (1.0 x 1.0 ft) section of Navy mattress (MIL-M-18351F(SH), 11 cm thick Safeguard polychloroprene foam core covered with a fire retardant cotton ticking) will be under a loose pile of bedding, including one polyester batting, quilted mattress pad (Volunteer Blind Industries, GS-07F-14865, DDD-P-56E), one bed sheet (Federal Specification DDD-S-281) and one brown bedspread (Fed Spec DDD-B-151) (each 0.6 x 0.6 m). A butane lighter will be used to ignite the top bedding material in the corner of the mattress.
4	Flaming Heptane Pan	200 ml of heptane will be burned in a 13 x 13 cm (5 x 5 in..) pan. A butane lighter will be used to ignite the pan. The amount of fuel is designed to yield an approximate burn time of 4.5 minutes.
5	Flaming Diesel-soaked Rags	Ten cotton rags, approximately 0.36 x 0.36 m (14 x 14 in..), each soaked with 30 ml of diesel fuel. A butane lighter will be used to ignite the pile.
6	Smoldering Bag of Trash	One plastic trash bag 61 x 84 cm O.D., 32 L, 6µm (24 x 33 in.. O.D., 12-16 gal) bag filled with ordinary office trash (10 sheets printer paper, 20 crumpled, brown paper towels, bubble wrap (1 ft x 4 ft), four FedEx letter mailing packs, five polystyrene plastic cups). One cartridge heater (Ogden model MWEJ05J1870, 700 W) energized at 120 VAC will be located beneath the closed bag, on top of a piece of gypsum board.
7	Smoldering Mattress and Bedding	The mattress and bedding mockup described in Fire Source No. 3 will be used. One cartridge heater (Ogden model MWEJ05J1870, 700 W) energized at 120 VAC will be located between the bedding and the mattress.
8	Smoldering Cable Bundle	Bundle of cable consisting of 5 pieces, each one foot in length (Monroe Cable Co., LSTSGU-9, M24643/16-03UN XLPOLYO). One 500 W cartridge heater (Vulcan, TB507A) placed in the middle of the bundle energized at 84 VAC (70% of 120 V max) will be the initial setting used. The power will be increased to 500 W (100%) after 25 to 30 minutes.
9	Smoldering Computer Monitor	A 15 inch standard computer monitor will be exposed to an internal heat source. One 500 W cartridge heater (Vulcan, TB507A) will be inserted into a 1.6 cm (0.6 in..) hole at the bottom corner of the monitor (either front or back). Using a variac, the cartridge heater will be energized to 80% of the 120 VAC supply.

Table 2 — Nuisance Sources

No.	Nuisance Source ID	Description
1	Torch Cut Steel	A 1.0 cm (3/8 in.) thick, 6.4 x 6.4 cm (2.5 x 2.5 in.) angle iron will be cut with an oxyacetylene torch.
2	Cutting Steel	A 1.0 cm (3/8 in.) thick, 6.4 x 6.4 cm (2.5 x 2.5 in.) angle iron will be cut with a metal cut off saw
3	Toaster: Normal Toasting	Four slices of white bread will be toasted in a Magic Chef (model N-10) 120V, 1500W toaster at the darkest setting for two cycles.
4	Welding	Two pieces of steel will be welded using an arc welder.
5	Grinding Painted Steel	A 0.6 x 0.6 m (2.0 x 2.0 ft) sheet of steel with 3 coats of paint (Navy Spec) will be ground with a 8.9 cm (3.5 in.) power hand grinder for approximately 5 minutes. The paint will be consistent with DOD-E-24607A chlorinated alkyd enamel paint color white (FED-STD-595 color No. 27880)
6	Grinding Cinder Block	A standard 8.9 cm (3.5 in.) power hand grinder will be used with a metal disk to grind a cinder block for approximately 5 minutes.

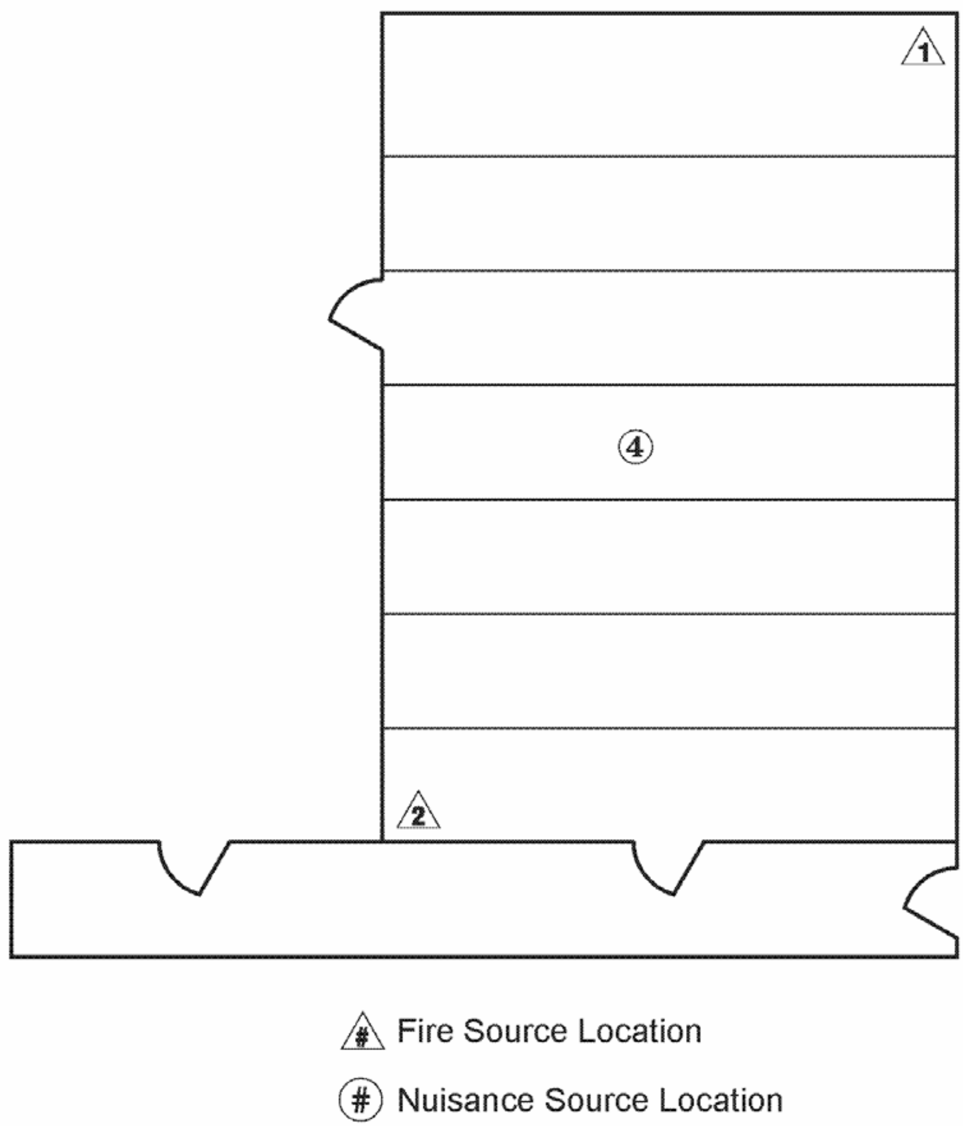

Fig. 6 — Fire and nuisance source locations

4.4 Detectors

The primary focus of this evaluation is on the Smart Chemical Microsensor array being developed by General Atomics. The performance of these detectors was compared to that of the multi-criteria and single sensor smoke detection systems. Details of the detection systems are given in Sections 4.4.1 and 4.4.2.

In general, the detector types and their respective locations in each test compartment were chosen to allow response of the different detection methods to be compared based upon complete systems with full space coverage. The smoke detectors were installed in general accordance with industry standards (i.e., NFPA 72 [10]). Each spot-type detector was mounted to a standard electrical box that was mounted directly to the overhead. A spacing of 0.3 m (1.0 ft) from center to center was maintained between detectors.

The detectors in the large compartment were located one-third of the way from the port and starboard bulkheads in bay 3 and bay 5, respectively, and an additional cluster of detectors was centered in bay 4, as seen in Fig. 7. The bays are numbered from forward to aft, where forward is represented by the bulkhead opposite the door leading to the passageway. This layout was used in previous test series [9]. The passageway had one detector cluster centered in the passageway. Figure 7 shows the approximate locations of the detectors to their respective instrumentation.

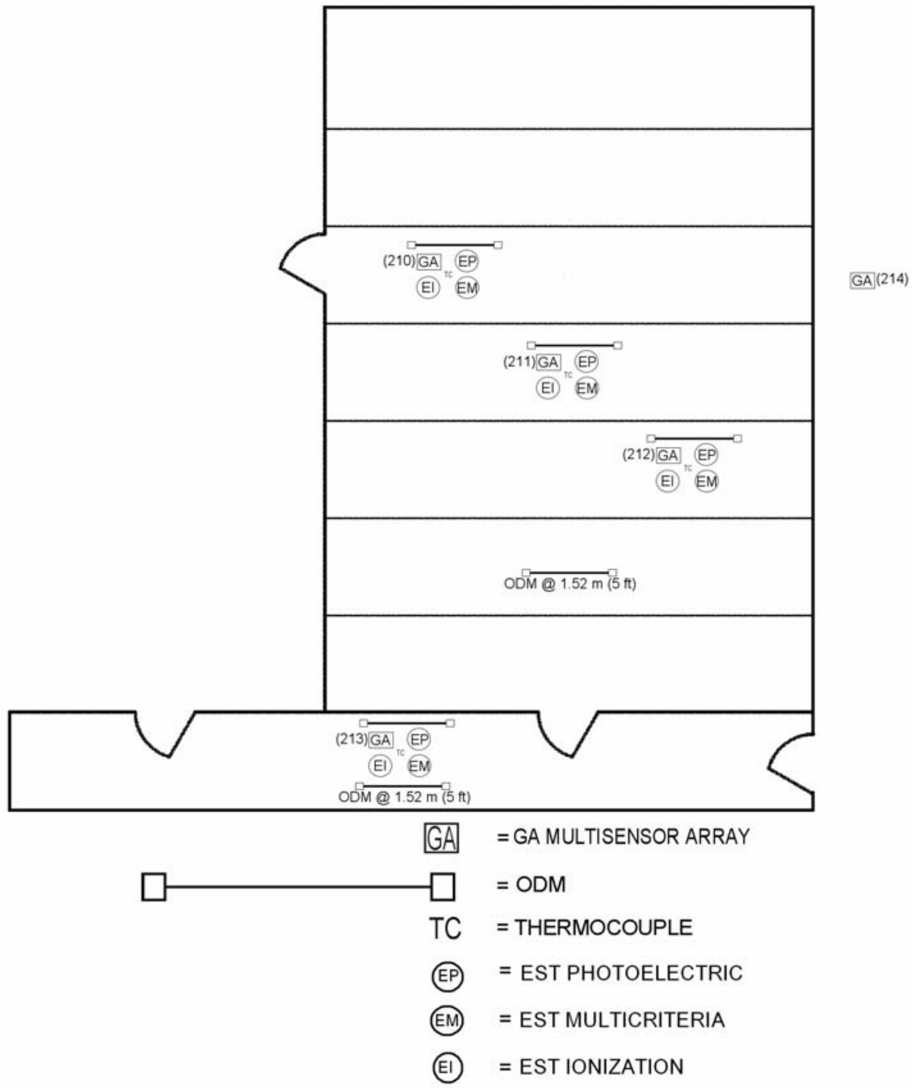

Fig. 7 — Detector and instrumentation locations

4.4.1 GA Microsensor Prototype

The GA microsensor prototype, shown in Fig. 8, is composed of a physical sensing system, graphical user interface software, and a 24 VDC power supply. The physical sensing system involves a microsensor array of economical, durable, high-temperature ceramic-metallic (cermet) sensor elements, shown in Fig. 9. An electrochemical (voltammetric) measurement technique will be used to generate the complex response waveform from the microsensors. Voltammetry involves applying a varying potential (typically a triangular waveform) across an electrochemical cell and measuring the resultant current. The electrical characteristics of an electrochemical cell (i.e. current vs. voltage response) are influenced by the presence of analyte gases.

Fig. 8 — GA smart microsensor prototype

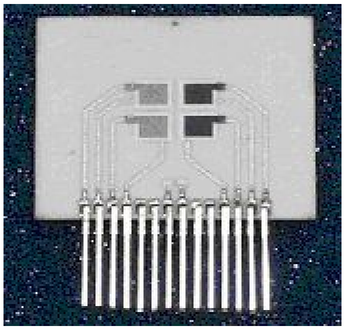

Fig. 9 — GA chemical microsensor array

The graphical user interface (GUI) software provided with the GA Smart Microsensor provides control of the device, real-time graphical representation of the data, and the ability to log the data to an ASCII text file. Various settings for the GA Smart Microsensor can be modified through the GUI. The default settings were used for all settings, with the exception of the sensor operating temperature and the step voltage (scan rate). A set point operating temperature of 260 °C and a scan rate of 400 mV/s were used for this test series, based on preliminary laboratory testing.

All five GA microsensor prototypes were connected to a single personal computer (PC) using an Ethernet network. Each unit was assigned a unique IP address that ended in the range 210 to 214 which was subsequently used as an identifier for each unit. Initially, all the detectors were collocated in bay 3 of the test space to determine if all units gave similar responses. The integral 24 VDC power supply in each prototype unit will require a standard 110 VAC source located near the unit. Under normal operating conditions, each GA Smart Microsensor requires approximately 10W of input power.

Data for each test was logged to an ASCII text file in comma separated values (CSV) format, which can be readily imported into common spreadsheet applications. Each data file was saved with the test name and detector unit incorporated into the filename. For example, the filename for the GA Smart Microsensor detector 212 in Test 9 was Test09Unit212.csv, where Test09 is the name of the test and Unit212 denotes the detector. For the 20 ms data record interval used in this test series, 145 KB of disk storage space per minute of data logged was required [11].

The data collected was predicted versus a training set comprised of previously collected laboratory data. The data collected was reduced from the 3000 point waveform using wavelet transformation models generated from the training data and then classified using a probabilistic neural network [12]. These methods for data reduction and prediction were applied to the TIC database and provided good results.

The data analysis was performed using routines written in MATLAB®, version 7.0 (Mathworks, Inc., Natick, MA). The MATLAB routines used for PCA were provided in the PLS_Toolbox, version 3.0.4 (Eigenvector Technologies, Inc., Manson, WA). The MATLAB routines for wavelet analysis were from Wavelab802 (http://www-stat.stanford.edu/~wavelab/). The classifier used in this study, probabilistic neural network (PNN) [13] was developed at the Naval Research Laboratory.

4.4.2 Commercial Smoke Detectors

Edwards System Technologies (EST) spot-type ionization, photoelectric, and multi-criteria detectors were installed in three clusters as shown in Fig. 7. All similar spot-type detectors in a space were considered as a system for a given test. For instance, if any of the EST ionization detectors in the space alarm, then the EST ion system was considered to have alarmed. The EST detectors were re-initialized before each test using a computer software program provided by EST and installed on a laptop. The EST devices evaluated included the multi-sensor ion-photo-heat (model SIGA-IPHS), the ionization (model SIGA-IS) and the photoelectric detectors (model SIGA-PS). The EST system detectors were monitored using a single EST3

alarm panel. This panel was configured per the manufacturer's recommendation. The EST detector response times were evaluated at their "Normal Sensitivity" settings. These settings are 8.0 % obsc/m (2.5 % obsc/ft) for the photoelectric units and 2.9 % obsc/m (0.9 % obsc/ft) for the ionization units.

4.5 Instrumentation

In addition to commercial fire alarm equipment, instrumentation was installed throughout the test compartments to measure temperatures and smoke density. Details on the instrumentation used for these measurements are discussed in Sections 4.5.1 and 4.5.2. The locations of the instrumentation are shown in Fig. 7.

4.5.1 Optical Density Meters

Smoke obscuration was measured using Optical Density Meters (ODMs). The white light ODMs consisted of a spot light and a photocell consistent with the specifications in UL 217, Standard for Single and Multiple Station Smoke Alarms [14]. The light source is a low-voltage spot lamp (GE 4515) spaced 1.5 m (5.0 ft) from a barrier layer photovoltaic cell (Hyugen 856-RR). The ODMs were positioned adjacent to each grouping of smoke detectors in both the compartment and passageway, as shown in Fig. 7, as well as in the center of the space at a height of 1.5 m (5 ft) above the deck.

4.5.2 Thermocouples

Type K, bare bead thermocouples were used to measure the overhead gas temperatures adjacent to the detectors. The thermocouples were positioned at the approximate height of the detector heads, 10 cm (4 inches) below the overhead.

4.6 Test Procedure

The general test procedure was to assure that all equipment was operational and that all system clocks were synchronized. The test was then conducted. Once the testing was complete the compartment was ventilated. The test space was cleared of smoke between tests via the exhaust ventilation system. Once the compartment and passageway were completely ventilated the next test began. The procedure included a check and establishment of a clean baseline for all systems between tests. For each test, the primary data acquisition system was started and allowed to collect background data for a minimum of 300 seconds. After the background data was collected, the source was initiated and allowed to continue until fully consumed or until all systems were in alarm or showed no change in detection due to quasi-steady state conditions.

4.7 Test Matrix

A total of 115 tests (70 fire tests, 28 nuisance tests, and 17 ammonia checks) were conducted over a two month period. The test matrix was designed to provide a range of fires sources, source locations, and ventilation conditions to comprehensively evaluate the detection systems against likely shipboard fire scenarios. On a prescribed periodic basis, the sensors were exposed to ammonia to assure consistent response verification of the units. In addition, the

heptane pool fire were conducted in location 1 on a periodic basis to establish a repeated quasi-calibration check of the detection systems to assess any changes over the course of the test series.

The portion of the test matrix dedicated to evaluating the nuisance source immunity of the detection systems aimed to provide worst-case nuisance scenarios in terms of source location. That is, the sources were close to the detectors so that the source was not diluted. The six nuisance sources were each tested at Location 3. Nuisance source tests were chronologically interspersed with the fire tests.

Table 3 lists tests 1 through 47 which were conducted with all the GA detectors collocated in bay 3 of the test space to determine if all units gave similar responses and to generate a training set for algorithm development. For tests 32 to 39, Unit 210 was not functioning.

The detectors were then moved to various locations in the test space as shown in Figure 7. Units 210, 211, and 212 were moved to bay 3, 4, and 5 respectively, while unit 213 was moved to the passageway. Unit 214 was moved outside the test space and was used to collect background air. Table 4 contains a list of the fire tests conducted when the units were moved to new locations. Unit 210 stopped functioning after Test 52 and was replaced by Unit 213 which was moved from the passageway to bay 3. Unit 214 also stopped working at that time and was removed from service.

Table 3 — Summary of laboratory tests with sensors collocated.

Test Number	Source description	Source Location	DAQ start	Source Initiation	Source transition	Source terminated	DAQ secured	Notes
Test 1	Heptane Pan Fire	1	7:58:00	8:03:00		8:09:10		
Test 2	Flaming Boxes	1	9:00:00	9:05:27		9:11:15	9:13:15	
Test 3	Flaming Trash Can	1	10:05:00	10:10:25		10:22:15	10:24:15	
Test 4	Flaming Mattress and Bedding	1	11:08:00	11:13:00		11:20:20	11:22:20	
Test 5	Flaming Diesel Soaked Rags	1	12:06:00	12:11:00		12:34:00	12:36:00	
Test 6	Smoldering Bag of Trash	1	14:07:00	14:18:00	14:23:20	14:30:45	14:33:45	
Test 7	Smoldering Cable Bundle	1	15:37:00	15:42:00		16:17:00	16:17:00	16:07:00 variac voltage increased to 100% (120 VAC)
Test 9	Heptane Pan Fire	1	7:50:00	7:55:10		8:00:00	8:02:00	
Test 10	Smoldering Mattress and Bedding	1	8:51:00	9:01:30	9:07:15	9:10:30	9:12:30	Power to Cartridge heater cut at 9:08:00
Test 11	Smoldering Computer Monitor	1	10:00:00	10:05:00	10:29:20	10:31:00	10:33:00	10:20:20 Cartridge heater moved, 10:26:30 Cartridge heater moved again
Test 12	Torch Cutting Steel	4	11:48:00	11:54:30		11:59:50	12:01:50	
Test 13	Welding	4	13:41:00	13:46:03		13:51:10	13:53:10	
Test 15	Heptane Pan Fire	1	9:37:00	9:42:00		9:47:20	9:49:20	
Test 16	Grinding Cinder Block	4	10:57:00	11:02:00		11:07:00	11:09:00	
Test 17	Grinding Steel	4	11:45:00	11:50:00		11:56:00	11:58:00	
Test 18	Grinding Painted Steel	4	14:17:00	14:22:00		14:27:00	14:29:00	
Test 19	Toast	4	16:13:00	16:18:00		16:23:00	16:25:00	
Test 21	Heptane Pan Fire	1	9:10:00	9:15:10		9:20:10	9:22:10	
Test 22	Heptane Pan Fire	1	8:24:00	8:29:00		8:34:05	8:36:05	
Test 23	Cutting Steel	4	9:41:00	9:46:00		9:51:00		Power trouble, overload in lab breaker shut down power.
Test 24	Flaming Boxes	1	10:28:00	10:33:05		10:39:30	10:42:00	
Test 25	Flaming Trash Can	1	11:32:00	11:37:05		11:45:00	11:47:00	
Test 26	Flaming Diesel Soaked Rags	1	13:43:00	13:48:00		14:06:05	14:08:05	

Table 3 — Summary of laboratory tests with sensors collocated. (continued)

Test Number	Source description	Location	DAQ start	Source Initiation	Source transition	Source terminated	DAQ secured	Notes
Test 28	Heptane Pan Fire	1	8:56:00	9:01:00		9:06:25	9:08:25	
Test 29	Welding	4	10:01:00	10:06:14		10:11:15	10:13:15	
Test 33	Toast	4	10:25:00	10:30:00		10:34:40	10:36:40	10:32:40 Cycle 1 ended, 10:34:10 and 10:34:40 cycle 2 ended respectively: GA sensor 210 not functioning
Test 34	Cutting Steel	4	11:07:00	11:12:00		11:17:15	11:19:15	GA sensor 210 not functioning
Test 35	Grinding Cinder Block	4	11:48:00	11:53:00		11:58:00	12:00:00	GA sensor 210 not functioning
Test 36	Grinding Painted Steel	4	12:28:00	12:33:00		12:38:00	12:40:00	GA sensor 210 not functioning
Test 37	Torch Cutting Steel	4	14:01:00	14:06:05		14:11:00	14:13:00	GA sensor 210 not functioning
Test 38	Cutting Steel	4	14:49:00	14:54:00		14:59:00	15:01:00	heptane telltail burning in subfloor GA sensor 210 not functioning
Test 39	Cutting Steel	4	15:51:00	15:56:05		16:01:00	16:03:00	GA sensor 210 not functioning
Test 41	Heptane Pan Fire	1	8:05:00	8:10:00		8:14:35	8:16:35	214 flatline was temperature setting issue, temperature setting in GUI was 0 to 260.
Test 42	Smoldering Cable Bundle	1	9:07:00	9:12:00		9:52:00	9:54:00	No ODM or TC data Smoke visible at 9:14:45 9:42:00 variac voltage increased to 100% (120 VAC)
Test 43	Flaming Mattress and Bedding	1	10:40:00	10:45:00		10:52:50	10:54:50	No ODM or TC data
Test 44	Smoldering Bag of Trash	1	11:45:00	11:50:00	11:52:10	12:00:00	12:02:00	No ODM or TC data Smoke visible at 11:50:50
Test 45	Smoldering Mattress and Bedding	1	13:25:00	13:30:00		13:58:00	14:00:00	No ODM and TC data Smoke visible at 13:32:00
Test 46	Smoldering Computer Monitor	1	16:38:00	16:43:00	16:46:00	16:58:00	17:00:00	No ODM and TC Data 16:45:30 Smoke visible Cartridge heater moved at 16:54:00

Table 4 — Summary of initial laboratory tests with sensors distributed in test space.

Test Number	Source description	Location	DAQ start	Source Initiation	Source transition	Source terminated	DAQ secured	Notes
Test 48	Heptane Pan Fire	1	8:40:00	8:45:00		8:50:15	8:52:15	Detectors spread out.
Test 49	Flaming Boxes	1	9:40:00	9:45:00		9:53:00	9:55:00	
Test 50	Flaming Boxes	1	11:55:00	12:00:00		12:07:30	12:09:30	
Test 51	Welding	4	14:09:00	14:14:00		14:19:00	14:21:00	First rod 14:14:00, second rod 14:15:30, third rod 14:17:00, fourth rod 14:18:30
Test 52	Smoldering Cable Bundle	1	14:59:00	15:04:00		15:32:00	15:34:00	Smoke visible at 15:06:00, variac increased to 100% 120 VAC at 15:30:00, Cartridge or fuse blew ending test
Test 54	Heptane Pan Fire	1	9:03:00	9:08:00		9:12:30	9:14:30	GA 214 not functioning
Test 55	Welding	4	9:51:00	9:56:00		10:01:00	10:03:00	Rod one done at 9:57:50, rod two done at 9:59:20 GA 210 and 214 not functioning
Test 56	Flaming Boxes	2	10:30:00	10:35:00		10:43:15	10:45:15	
Test 57	Smoldering Cable Bundle	2	11:26:00	11:31:00		12:02:30	12:04:30	11:58:00 VAC increased to 100% 120 VAC then fuse blew ending test. GA 210 and 214 not functioning
Test 58	Heptane Pan Fire	2	13:58:00	14:03:00		14:07:00	14:09:00	
Test 59	Grinding Cinder Block	4	14:40:00	14:45:00		14:53:00	14:55:00	Grinding blade broke had to start with new grinder at 14:47:00
Test 61	Heptane Pan Fire	1	8:55:00	9:00:00		9:04:30	9:06:30	GA sensor 213 moved from passageway to Bay 3
Test 62	Toast	4	9:47:00	9:52:00		9:56:35	9:58:35	Cycle one ended at 9:54:40 and 9:54:45, cycle two ended at 9:56:35 and 9:55:50
Test 63	Torch cutting Steel	4	10:39:00	10:44:00		10:49:10	10:51:10	
Test 64	Cutting Steel	4	11:35:00	11:40:15		11:45:15	11:47:15	
Test 66	Heptane Pan Fire	1	10:45:00	10:50:00		10:54:30	10:56:30	
Test 67	Flaming Trash Can	2	11:50:00	11:55:00		12:05:00	12:05:00	
Test 68	Flaming Trash Can	1	15:53:00	15:58:00		16:06:00	16:08:00	

Table 4 — Summary of initial laboratory tests with sensors distributed in test space. (continued)

Test Number	Source description	Location	DAQ start	Source Initiation	Source transition	Source terminated	DAQ secured	Notes
Test 70	Heptane Pan Fire	1	8:32:00	8:37:00		8:41:25	8:43:25	No DAQ, GA sensors 210 and 214
Test 71	Smoldering Trash	1	9:25:00	9:30:00	9:32:10	9:44:00	9:44:00	
Test 72	Smoldering Trash	2	11:35:00	11:40:00	11:44:00	11:52:30	11:54:30	
Test 73	Diesel Soaked Rags	1	13:40:00	13:45:00		13:55:00	13:57:00	
Test 74	Sub-Floor Cable burn	5	14:50:00	14:54:30	15:07:15	15:10:00	15:12:00	Smoke visible at 14:57:00 Agent (Firepro) released at 15:08:16
Test 75	Diesel Soaked Rags	2	16:23:00	16:28:00		16:41:00	16:43:00	
Test 77	Heptane Pan Fire	1	10:04:00	10:09:00		10:13:30	10:15:30	
Test 78	Flaming Boxes	2	11:56:00	12:01:00		12:10:10	12:12:10	
Test 79	Flaming Trash Can	2	13:49:00	13:54:00		14:05:00	14:07:00	
Test 80	Flaming Trash Can	1	14:56:00	15:01:00		15:10:45	15:12:45	
Test 82	Heptane Pan Fire	1	8:36:00	8:41:00		8:45:45	8:47:45	
Test 83	Smoldering Mattress and Bedding	1	9:32:00	9:37:00		10:17:00	10:17:00	
Test 84	Smoldering Mattress and Bedding	2	11:12:00	11:17:00	11:25:00	11:29:00	11:36:00	Small flame appeared at time of transition but died a few seconds later. Source terminated due to fuse failure.
Test 85	Flaming Trash Can	1	14:04:00	14:09:00		14:17:00	14:19:00	
Test 86	Heptane Pan Fire	2	14:49:00	14:54:00		14:59:00	15:01:00	GA sensor 213 ambient temperature reading high ~67°C other two GA sensor reading ~38°C
Test 87	Flaming Trash Can	2	15:37:00	15:42:00		15:52:00	15:54:00	
Test 89	Heptane Pan Fire	1	7:43:00	7:48:00		7:52:35	7:54:35	
Test 90	Flaming Boxes	1	8:56:00	9:01:00		9:10:00	9:12:00	
Test 91	Flaming Mattress and Bedding	1	13:42:10	13:48:00		13:50:00	13:52:00	
Test 92	Flaming Mattress and Bedding	2	14:27:00	14:32:00		14:33:10	14:35:10	
Test 93	Smoldering Mattress and Bedding	1	15:23:00	15:28:00		15:41:00	15:43:00	GA Sensor 213 ambient temp still reading high ~66°C, GA sensor 212 right top two graphs not functioning.
Test 95	Heptane Pan Fire	1	8:41:00	8:46:00		8:50:35	8:52:47	

Table 4 — Summary of initial laboratory tests with sensors distributed in test space. (continued)

Test Number	Source description	Location	DAQ start	Source Initiation	Source transition	Source terminated	DAQ secured	Notes
Test 96	Smoldering Mattress and Bedding	2	9:32:00	9:37:00	10:09:20	10:10:30	10:12:30	GA Sensor 213 ambient temp reading high ~67°C, 212 sensor top right graph working intermittently.
Test 97	Diesel Soaked Rags	1	11:00:00	11:05:00		11:21:00	11:23:00	
Test 98	Diesel Soaked Rags	2	12:09:00	12:14:00		12:26:00	12:28:00	GA sensor 213 ambient temperature rising ~132°C
Test 99	Sm. Cable Bundle	1	14:00:00	14:05:00	14:34:10	14:38:20	14:40:20	
Test 100	Sm. Cable Bundle	2	15:17:00	15:22:00	15:38:00	15:40:15	15:42:15	
Test 102	Heptane Pan Fire	1	9:08:00	9:13:00		9:17:50	9:19:50	GA sensor 213 ambient fault ~400°C, GA sensor 212 top right graph not functioning (flat-lined)
Test 103	Smoldering Trash	2	10:05:00	10:12:00	10:14:20	10:22:50	10:25:50	
Test 104	Smoldering Trash	1	11:14:00	11:19:25	11:21:45	11:33:45	11:35:45	Firepro suppressant in air
Test 105	Flaming Mattress and Bedding	2	15:58:00	16:03:00		16:06:00	16:08:00	
Test 107	Heptane Pan Fire	1	8:33:00	8:38:00		8:42:40	8:44:40	GA sensor 213 Ambient tamp error
Test 108	Flaming Mattress and Bedding	1	9:36:00	9:41:00		9:42:45	9:45:00	
Test 109	Toast	4	10:12:00	10:17:00		10:21:40	10:26:30	10:17:00 Start first cycle; 10:19:45 all four pieces popped up at end of cycle; 10:19:45 started second cycle; 10:21:05 end second cycle for two pieces (smoke visible; 10:21:40 second cycle ends for final two pieces.
Test 110	Torch cutting Steel	4	11:11:00	11:20:35		11:26:00	11:28:00	11:22:10 stopped and started again at 11:22:30, had trouble with the torch but realistic scenario
Test 111	Cutting Steel	4	11:54:00	12:00:00		12:05:00	12:07:00	
Test 112	Grinding Cinder Block	4	13:43:00	13:48:00		13:54:00	13:56:00	
Test 113	Grinding Painted Steel	4	14:18:00	14:23:00		14:28:00	14:30:00	
Test 114	Grinding Painted Steel	4	14:51:00	14:56:00		15:01:00	15:03:00	
Test 115	Smoldering Computer Monitor	1	15:28:00	15:33:00		16:06:00	16:08:00	

5.0 ALGORITHM DEVELOPMENT

The data was collected at 8 mV intervals resulting in 750 points for each voltammogram with a total of 3000 points for all four sensors. The data was background subtracted using the five scans prior to ignition. The times used to generate the training set came from the alarm time of the EST multi-criteria detectors. If the multi-criteria detector did not alarm then the times for the ionization detector was used, or if it did not alarm the pattern chosen was approximately two minutes into the test. Background patterns were taken at just prior to ignition and at approximately 2 minutes after the start of data acquisition.

Wavelet transformation was used for data reduction and feature selection. Wavelet transformation of cermet microsensor array data provides two principal advantages: data compression and enhanced feature selection. A wavelet transformation takes data from a time domain to a scale-dependant frequency domain. Varying this scale allows for a series wavelet coefficients to describe frequency-based features in the data that are also localized at specific times. Data compression is achieved by selectively filtering out coefficients from the wavelet transform that contain little or no signal. Feature selection is achieved by locating coefficients that contain information relevant to a desired classification.

For the cermet data, a Daubechies 8 wavelet function was chosen for study. The Daubechies wavelet is commonly used in similar applications and is well suited to describing the broad features located in the spectra output by cermet microsensor array. Prior to transformation, the spectra from each sensing element are separated and extended to dyadic length as required by the fast wavelet transform algorithm. This was accomplished by expanding the waveform from 3000 to 4096 points. An analysis of variance (ANOVA) was used to downselect the coefficients to 64 wavelet coefficients. The training data was divided into three classes: non-fires, flaming fires and smoldering fires. The fires were split into two categories so that differences between flaming and smoldering fires could be maintained in the data space. Figure 10 shows the ANOVA ratios used to determine which coefficients were used. Figure 11 shows a Principal Component Analysis (PCA) plot of the training data using the first 2 principal components which accounts for 83% of the variance in the data.

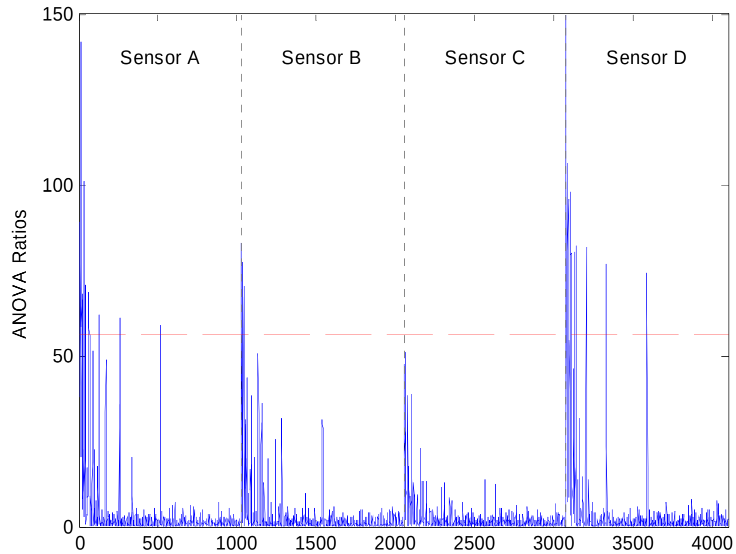

Fig. 10 — ANOVA ratios used for feature selection.

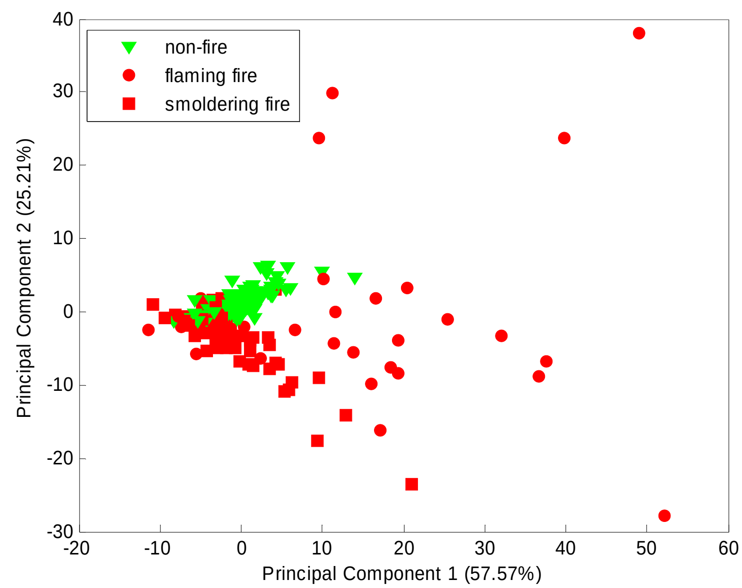

Fig. 11 — PCA plot of training data.

The data from the first 47 tests, when the sensors were clustered together, was used to build a training set that was validated with the data from the next 58 tests. For each test being predicted the patterns generated on all of the detectors from that test were removed from the training data and predicted from the remaining data. From this data a probability cutoff of 90% was seen as giving the best fire classification versus the false alarm rate as determined by ROC curve, Figure 12.

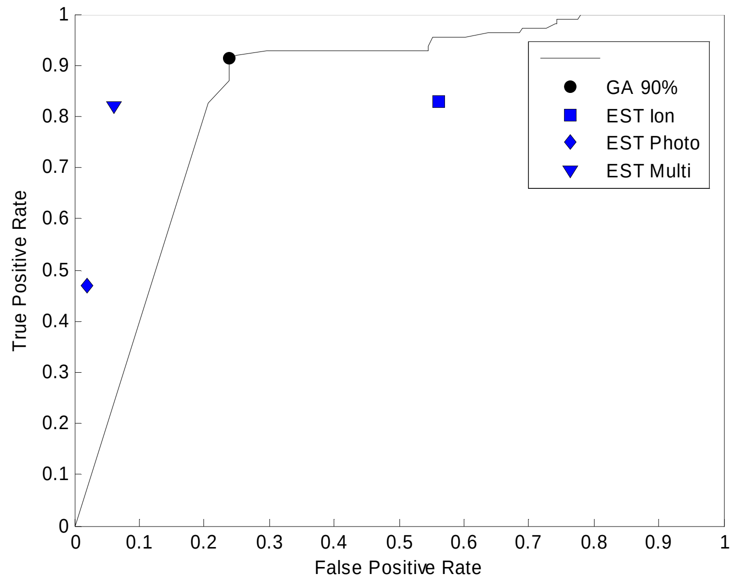

Fig. 12 — Training data ROC curve comparing GA Smart Microsensor vs. EST detectors.

6.0 MEASURES OF PERFORMANCE

Two measures of performance will be used to evaluate the smoke detectors:

1. Alarm time
2. Percent correct classification of fire and nuisance sources

All detectors will be considered as part of a system for the entire test facility. For instance, if any of the three EST ionization detectors installed alarm, then the EST ion system is considered to have alarmed. In this manner, a multi-criteria detection system will be compared to the GA system (i.e., three devices) and to the corresponding manufacturer's ionization system and photoelectric system. In addition, a combined ion-photo system will be evaluated since this is a practice that has been employed by the Navy. The combined ion-photo system will include one ion and one photo (each at a different group location) and a photoelectric unit in the passageway.

7.0 RESULTS

Table 5 lists the alarm times for the General Atomics Smart Microsensor and the three spot-type detector technologies (ion, photo, and multicriteria). The times are recorded in seconds after ignition of the source. The test numbers as well as a brief description are listed in column 1 and 2. GA Smart Microsensors alarm times (at 90% probability) are listed in column 3. The EST spot-type detector alarm times are listed in the remaining three columns, 4 through 6. A listing of DNA means the system did not alarm.

Table 5 — Comparison of alarm times for GA Smart Microsensor versus EST Detectors.

Test Number	Source description	GA	EST Ion	EST Photo	EST Multi	EST Ion/Photo
Test 48	Heptane Pan Fire	112	**83**	DNA	239	**83**
Test 49	Flaming Boxes	150	**96**	DNA	287	**96**
Test 50	Flaming Boxes	189	**119**	162	165	**119**
Test 51	Welding	**240**	42	70	72	42
Test 52	Sm. Cable Bundle	**334**	DNA	526	763	526
Test 54	Heptane Pan Fire	145	**84**	199	160	**84**
Test 55	Welding	240	86	52	**DNA**	52
Test 56	Flaming Boxes	**131**	137	165	164	137
Test 57	Smoldering Cable Bundle	**227**	DNA	788	1646	788
Test 58	Heptane Pan Fire	146	**59**	153	104	**59**
Test 59	Grinding Cinder Block	196	**DNA**	480	588	480
Test 61	Heptane Pan Fire	99	**82**	195	146	**82**
Test 62	Toast	194	217	273	**283**	217
Test 63	Torch cutting Steel	156	24	**DNA**	161	24
Test 64	Cutting Steel	295	**DNA**	**DNA**	**DNA**	**DNA**
Test 66	Heptane Pan Fire	118	**72**	207	141	**72**
Test 67	Flaming Trash Can	78	**52**	247	213	**52**
Test 68	Flaming Trash Can	168	**75**	512	446	**75**
Test 70	Heptane Pan Fire	181	**74**	204	142	**74**
Test 71	Smoldering Trash	207	169	**163**	179	**163**
Test 72	Smoldering Trash	285	267	**263**	281	**263**
Test 73	Diesel Soaked Rags	129	81	**79**	89	**79**
Test 74	Sub-Floor Cable burn	537	**430**	445	500	**430**
Test 75	Diesel Soaked Rags	100	69	**67**	76	**67**
Test 77	Heptane Pan Fire	114	**84**	222	146	**84**
Test 78	Flaming Boxes	167	**157**	197	190	**157**
Test 79	Flaming Trash Can	176	**94**	391	268	**94**
Test 80	Flaming Trash Can	167	**87**	331	285	**87**
Test 82	Heptane Pan Fire	80	**79**	247	163	**79**
Test 83	Smoldering Mattress and Bedding	**207**	948	388	460	388
Test 84	Smoldering Mattress and Bedding	**283**	DNA	306	410	306
Test 85	Flaming Trash Can	132	**76**	173	133	**76**
Test 86	Heptane Pan Fire	DNA	**49**	148	107	**49**
Test 87	Flaming Trash Can	129	**92**	416	478	**92**
Test 89	Heptane Pan Fire	176	**94**	233	164	**94**
Test 90	Flaming Boxes	225	**156**	230	202	**156**
Test 91	Flaming Mattress and Bedding	DNA	DNA	DNA	DNA	DNA

Table 5 — Comparison of alarm times for GA Smart Microsensor versus EST Detectors. (continued)

Test Number	Source description	GA	EST Ion	EST Photo	EST Multi	EST Ion/Photo
Test 92	Flaming Mattress and Bedding	DNA	DNA	DNA	DNA	DNA
Test 93	Smoldering Mattress and Bedding	355	403	**324**	488	**324**
Test 95	Heptane Pan Fire	99	**81**	223	150	**81**
Test 96	Smoldering Mattress and Bedding	271	1331	**268**	692	**268**
Test 97	Diesel Soaked Rags	234	**66**	76	89	**66**
Test 98	Diesel Soaked Rags	134	67	**63**	69	**63**
Test 99	Smoldering Cable Bundle	**577**	1926	728	1675	728
Test 100	Smoldering Cable Bundle	**403**	DNA	573	DNA	573
Test 102	Heptane Pan Fire	**65**	85	233	159	85
Test 103	Smoldering Trash	223	**198**	270	257	**198**
Test 104	Smoldering Trash	**237**	242	444	353	242
Test 105	Flaming Mattress and Bedding	**45**	DNA	DNA	DNA	DNA
Test 107	Heptane Pan Fire	87	**71**	224	157	**71**
Test 108	Flaming Mattress and Bedding	DNA	DNA	DNA	DNA	DNA
Test 109	Toast	280	**DNA**	**DNA**	**DNA**	**DNA**
Test 110	Torch cutting Steel	-248	19	**DNA**	**DNA**	19
Test 111	Cutting Steel	**DNA**	**DNA**	**DNA**	**DNA**	**DNA**
Test 112	Grinding Cinder Block	**DNA**	**DNA**	**DNA**	**DNA**	**DNA**
Test 113	Grinding Painted Steel	**DNA**	**DNA**	**DNA**	**DNA**	**DNA**
Test 114	Grinding Painted Steel	**DNA**	**DNA**	**DNA**	**DNA**	**DNA**
Test 115	Smoldering Computer Monitor	**318**	DNA	1069	DNA	1069

Periodic exposures to ammonia were conducted throughout the test series. The ammonia exposures were run as tests 8, 14 20, 27, 40, 47, 53, 60, 65, 69, 76, 81, 88, 94, 101, 106 and 116. The data for each detector was checked to see if the sensor responses changed over the course of testing. Only minor changes in magnitude were seen in the sensor responses over time. This was probably a combination of the fire tests and the household ammonia used that was not necessarily a constant concentration over time.

The sensors were also checked for stability by the heptane pool fires which were conducted in location 1 on a periodic basis. In the initial testing when the detectors were collocated, it is assumed each unit saw the event similarly. The detector responses from the heptane pool fires were consistent with each other over the course of the testing.

One major issue seen was with the electronics used to run the detectors. After test 86 one unit had an elevated ambient temperature reading versus the other units running. One issue with the sensors used in this test was a shorting/spiking problem. This was determined to be caused by the tungsten bismuth oxide (WBO) as the top layer in contact with the palladium electrode. After the test series all the units were returned to General Atomics to investigate the electronics problems.

8.0 DISCUSSION

The following measures of performance were used to evaluate and compare the different detection technologies:

1. Percent correct classification.
2. Speed of response.

8.1 Source Classification

Table 6 shows the comparison of each detectors classification. The GA Smart Microsensor detectors are able to pick up most of the fires that were tested, especially the smoldering fires, which Table 7 shows as being detected faster than the EST detectors. The smoldering fires are emitting vapors that are based on the smoldering material that is being used. This is most likely due to the better chemical detection capability the cyclic voltammetry has over the simple ionization or photoelectric methods the EST detectors use. For three of the flaming fires that the GA Smart Microsensor detectors missed, the EST systems also did not detect a fire. In Test 110 only two GA Smart Microsensor units were still operating. Both units alarmed before the test began shortly after the start of data collection. Visual inspection of the voltammograms shows an offset from the tests before or after. The sensors may not have had enough time to equilibrate before the test began.

At this time nuisance sources are frequently misclassified as fires. However, half of the missed nuisance events were welding or the use of an acetylene torch. These events are generating vapors or combustible products that are similar to a fire. More work is needed to extract features that can discriminate these events. One approach is to have better representation of theses fire-like events in the training set. In the current training set these events are 25% of the nuisance types and 10% of the overall dataset. The training may need to be weighted more for these events to help achieve better discrimination.

Table 6 — Summary of Events Correctly Identified by the Smart Microsensor and the Commercial Fire Detection Systems

Event Type	Smart Microsensor	Ionization	Photoelectric	Multi-criteria	Ion/Photo
Flaming	88%	88%	82%	88%	88%
Smoldering	100%	62%	100%	84%	100%
Nuisance	33%	58%	67%	67%	50%

8.2 Time to Alarm

The performance of the GA Smart Microsensor system was compared to the performance of the commercial EST spot-type detectors. The performance was evaluated based on the ability

to correctly classify events and on the response time of the system. Table 7 shows a comparison of the alarm times for each of the EST detectors relative to the GA Smart Microsensor System. A comparison was made only if both detectors alarmed for a given test. A time was considered similar if the difference was less than 30 seconds. The GA Smart Microsensor System was the first to alarm in a majority of the tests, except for flaming fires versus the ionization detector.

Table 7 — Comparison of GA alarm times versus EST Detectors for fires.

Fire Type	Number of Events	Ion	Photo	Multi	Ion/Photo
Flaming	Faster	0	16	14	0
	Similar	9	4	8	9
	Slower	18	5	6	18
Smoldering	Faster	4	8	9	6
	Similar	3	3	2	5
	Slower	1	2	0	2

The average time to alarm for the flaming fires was 135 seconds for the GA system versus 86, 215, and 183 seconds for the EST ionization, photoelectric and multicriteria respectively. The average time to alarm for the smoldering fires was 319 seconds for the GA system versus 657, 468, and 642 seconds for the EST ionization, photoelectric and multicriteria respectively.

9.0 PERFORMANCE SUMMARY

The test series successfully demonstrated the functionality and performance of the GA Smart Microsensor system for use in fire detection. Based on the test series and this initial analysis, the following conclusions are presented:

- The GA system demonstrated the ability to detect flaming and smoldering fires at the same level as the commercial multi-criteria detector.
- The GA system had mixed results compared to the conventional detection methods, such as state-of-the-art, COTS spot-type smoke detectors in time to alarm after source initiation. The GA system was on average 2.5 to 5.5 minutes faster for smoldering fires, versus all detector types, and 50 to 80 seconds faster for flaming fires, versus multi-criteria and photoelectric detectors, but 50 seconds slower than the ionization detector.
- The GA system needs improvement in addressing fire-like events such as welding or the use of an acetylene torch.

10.0 CONCLUSIONS

The results of this test series indicate that cermet sensors are promising fire detectors. Areas of improvement have been identified. The algorithms developed from this testing will be validated by shipboard testing conducted onboard the ex-USS *Shadwell*. Future work will also involve incorporation of TIC algorithms to expand the system capabilities.

Work is continuing with General Atomics to incorporate the algorithms and data processing in the detectors to allow for a real-time continuous monitoring of the system. Investigation of the sensors themselves is underway to develop a method for knowing when the sensors have stabilized and data analysis can begin. This will allow for a more autonomous system.

Cermet sensors are powerful for the detection of toxic chemicals. Success in this program will result in one system capable of detecting fires and hazardous chemicals. It would be a big asset in protecting ships and facilities.

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